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Final Report: "AlGaN-GaN Heterostructure Field-Effect Transistors Grown by MOCVD"
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Program Objectives

The primary objectives of this program were to develop materials growth processes and epitaxial device structures for the improved performance of AlGaN/GaN-based heterostructure field-effect transistor (HFET) and to deliver HFET epitaxial structure for device fabrication and testing. We have used metalorganic chemical vapor deposition (MOCVD) for the growth of the device structures. Materials growth studies were performed at the Georgia Institute of Technology (P.I. Dr. R. D. Dupuis) and the results are reported to Kyma Technologies.

Research Activity Summary at Georgia Institute of Technology

In this program, we have investigated mainly two effects on HFET performance characteristics: one is the effect of modulation doping of Si in AlGaN layer and the other is Fe doping near the regrowth interface. The materials were grown by MOCVD in a reactor system equipped with close-coupled showerhead chamber (manufactured by Thomas Swan Scientific Equipment) using precursors of TMGa (trimethylgallium), TMAl (trimethylaluminum), NH_3, SiH_4 (10ppm balanced in H_2) and Cp_2Fe (ferrocene (bis(cyclopentadienyl)iron)) in H_2 carrier gas. The substrate used for calibration and device structures were sapphire, SiC, and free standing GaN substrates.

Figure 1 shows the schematic epitaxial structures of HFETs in this study. Note that the structures employ AlN binary barrier (~1nm) and modulation doping of Si (~2nm) in AlGaN spacer layer (~29nm). Also the HFET structure included Fe doping near the regrowth interface to remove the interface charge, which will be discussed later. First, the concentration of Si modulation doping is changed to study the effect of modulation doping on the electrical transport properties of 2-DEG (2-dimensional electron gas). Three HFET structures were prepared with different Si concentration: 2-0881 with SiH_4 flow rate=50sccm; 2-882 with SiH_4 flow rate=15sccm; 883 with SiH_4 flow rate=3sccm. The doping concentrations of modulation doping are estimated to be $1.3\times10^{19}cm^{-3}$, $4\times10^{18}cm^{-3}$, and $8\times10^{17}cm^{-3}$ for 2-881, 2-882, and 2-883, respectively. As the concentration of modulation doping increases, mobility of 2-DEG decreases and sheet carrier density increased, resulting in decrease in sheet resistance and increase in the product of mobility and sheet carrier density, as shown in Table I. However, excessive Si modulation doping might cause problems in transistor operation. The HFET structures with modulation doping were characterized by mercury-probe capacitance-voltage (C-V) measurement using both front contact geometry. The structures show a sudden increase in capacitance near pinch-off voltage, which might be associated with surface leakage during the measurement.

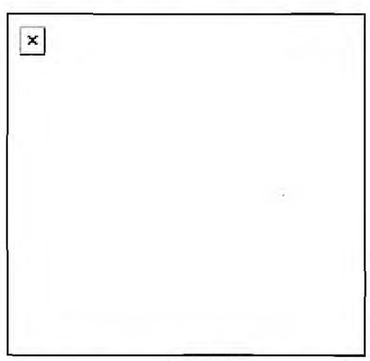


Figure 1: Schematic epitaxial structures of HFETs employing AlN binary barrier and Si modulation doping in AlGaN spacer in this study.

Table I. Electrical properties of HFETs with different Si modulation doping concentration

Second, we focused on the control of interface charge with different Fe-doped GaN layers.[1] For the GaN/sapphire template growth, the initial GaN layer is unintentionally doped, that is, Fe doping was not introduced near the GaN-sapphire substrate interface, in order that the charge at the interface of the GaN template and the sapphire substrate can be used as a marker for C-V measurements. In order to investigate the effect of the Fe doping at the re-growth interface, three HFET samples with different Fe doping schemes at the re-growth interface were prepared: GaN:ud (#877), 50-nm thick GaN:Fe (#884), and 280-nm thick GaN:Fe (#885) grown on the ~2-μm GaN:ud templates with same layer thickness (~2 μm) and crystalline quality in the HFET structures, as shown in Figure 2.

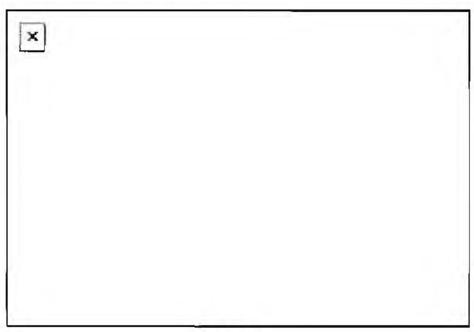
(a) (b)

Figure 2: Schematic diagram of the HFET structures with (a) undoped GaN layer (#877), and (b) Fe-doped GaN layer (# 884 and #885) at the re-growth interface grown on an undoped GaN/sapphire template.

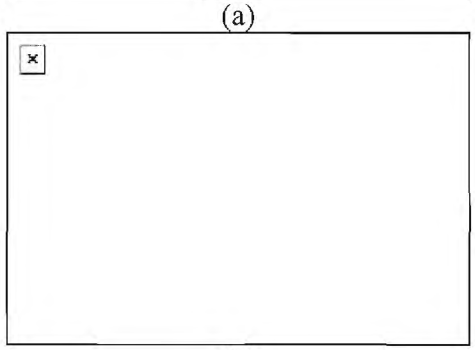
Figure 3 (a) shows the SIMS depth profiles of the HFET structures without a GaN:Fe layer (#877). It is found that Si impurities with a concentration of $\sim 2\times10^{18}$ cm^{-3} are incorporated at the re-growth interface even though the structure does not have any Si doping in the bottom layer before the growth of the HFET structure. Also, the thickness of the unintentional Si-doped layer is estimated to be ~50 nm. Other impurity-related peaks such as C and O are not detected at the re-growth interface using our surface preparation conditions prior to the re-growth. For the compensation of unintentional Si-doped layer at the re-growth interface, a GaN layer with $[Fe]>2\times10^{18}$ cm^{-3} having the thickness of 50 and 280 nm was introduced during the initial re-growth of GaN. The influence of different Fe doping at the re-growth interface in the HFET structures as determined by C-V profiling is shown in Figure 4 (a). These C-V profiles show that well-defined 2-DEGs are created at the AlGaN/AlN/GaN interface. Comparing the charge associated with the re-growth interface, the interface charge is observed at a depth of ~2 μm, which corresponds to the re-growth interface, for the HFET structure #877 and #884, while no

[1] The results were also published in Applied Physics Letters: W. Lee, J. H. Ryou, D. Yoo, J. Limb, R. D. Dupuis, D. Hanser, E. Preble, N. M. Williams, and K. Evans, "Optimization of Fe doping at the re-growth interface of GaN for the applications to III-nitride-based heterostructure field effect transistors," *Appl. Phys. Lett.* **90**, 093509-1-3 (2007).

such charge accumulation is observed for #885. Compensation of the Si impurities by Fe doping was expected for both HFET structures #884 and #885, since both of them, in principle, have a large enough thickness and concentration of the GaN:Fe layer for compensation. To further investigate the difference between #884 and #885, the SIMS depth profiles were measured again and they are shown in Figure 3 (b) and (c). For both profiles, a "delayed turn-on" of Fe is observed, that is, [Fe] gradually increases as the growth proceeds even when using the same precursor inputs from the beginning of the growth. This delayed turn-on can be explained by (i) a "reactor surface saturation effect" as is typically also observed with Cp2Mg (bis(cyclopentadienyl)magnesium) or by (ii) the segregation of the Cp_2Fe precursor or Fe atoms before being incorporated into the lattice at the growth surface . Also, we believe that the "tailing off" of the Fe profile is not related to the Fe diffusion, since tailing does not go deeper beyond Si-related peak, which is located at re-growth interface. As a result of delayed turn-on, the structure #884 does not have enough Fe doping to fully compensate the Si at the re-growth interface, while wafer #885 has a similar Fe concentration to the Si concentration at the interface. The peaks for the Fe concentration and the Si concentration are not located at the same position but we think that the integrated Fe concentration and the Si peak are approximately within a Debye length so that effective compensation can occur. For complete compensation of the unintentional incorporation of Si at the re-growth interface, proper thickness of Fe-doped layer as well as concentration of Fe is required due to the delayed turn-on effect of the Fe doping. We also note a decreased Si auto-doping at the re-growth interface for HFET structure #885 as compared to #877. This can be ascribed to SIMS calibration issues or reactor condition changes. However, we also consider the possibility that Fe doping, besides affecting the electrical compensation of Si, could also affect the Si dopant incorporation through a lattice site competition mechanism between Fe and Si atoms.



(a)



(b)

(c)

Figure 3: SIMS profiles of Fe, Si, and other impurity concentrations of the HFET structures having different Fe doping schemes: (a) undoped GaN layer (#877), and (b) 50-nm thick Fe-doped layer (#884), and (c) 280-nm thick Fe-doped layer (#885) at the re-growth interface grown on undoped GaN template.

Figure 4: (a) Charge concentration vs. penetration depth profiles as determined by capacitance-voltage (C-V) measurements for the HFET structures with an undoped GaN layer (#877), a 50 nm thick Fe-doped GaN layer (#884), and a 280 nm thick Fe-doped GaN layer (#885) at the re-growth interface with voltage range to -6 V. (b) C-V characteristic of the HFET structure with a 280-nm thick Fe-doped GaN layer (#885) at the re-growth interface with a voltage range to -10.

Our data also show the effect of the Fe doping at the re-growth interface on the sheet carrier concentration in the AlN/GaN interface, as shown in Figure 4 (a). The data for HFET structures #877 and #884 indicate almost equal concentrations of charge in the AlN/GaN interface due to 2-DEG and the charge at the re-growth interface due to unintentional incorporation of Si, even though #884 HFET structure has 50-nm GaN:Fe layer at the regrowth interface. However, HFET structure #885 shows a much higher charge accumulation at the AlN/GaN interface as well as no charge accumulation at the re-growth interface. The origin of higher charge accumulation for #885 is currently being investigated. The mobilities at 300 K by large-area Hall effect measurements for #877, #884, and #885 HFET structures are determined to be 1380, 1660, and 1750 cm2/Vs, respectively. The improved mobility may be associated with the effect of the GaN:Fe layer. Figure 4 (b) shows the C-V plot and charge concentration-depth profile of the HFET sample #885. The expected shape was observed, where the capacitance was found to be roughly constant while the 2-DEG was present, falling to essentially zero once the 2-DEG had been fully depleted and demonstrating full depletion of the GaN with no free carriers at the GaN/sapphire interface. Pinch-off at around -3.6 V is shown. As the measurement voltage increases -10V, charge accumulation in the GaN/sapphire is shown due to the impurities Si and O (Fe doping was intentionally not introduced near the GaN-sapphire substrate interface, as described earlier).

Based on the calibration and investigation performed, we have grown three FET structures on GaN substrates and one HFET structure on a SiC substrate and they were delivered to Kyma Technologies for device fabrication and testing.